Time to make multisensory research mobile

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Cognition is embodied and walking is a crucial body movement

For over a century, the investigation of human cognition has been mainly conducted in experiments with highly controlled sensory input in a stationary state, with maximal body movement suppression. Such carefully designed experiments played a crucial role in revealing the fundamental cognitive processes and underlying mechanisms, with confounding variables being controlled and high signal-to-noise ratio neural data being acquired. Notably, as suggested by embodied cognition, human cognitive processes are intricately linked with the interaction between the body and the environment (Byrge, Sporns, & Smith, 2014; Chiel & Beer, 1997; Wilson, 2002). A very important way humans interact with the environment is through body movement. However, laboratory settings may fail to capture these interactions, therefore the role of body movement in cognition being largely overlooked.

Among the numerous body movements, walking, in particular, has historically played a crucial role in validating mobile brain/body imaging (MoBI) techniques. These techniques were developed to address the challenges of recording EEG data during movement and have served as tests for signal processing approaches to correct the noise in EEG data recorded while subjects walked on a treadmill (Debener, Minow, Emkes, Gandras, & De Vos, 2012; Gramann, Gwin, Bigdely-Shamlo, Ferris, & Makeig, 2010). More importantly, walking is pervasive, complex, and highly functional. Failures in walking can have dire consequences, such as aging populations facing increased hospitalization risks and patients with locomotor disorders struggling to navigate and interact with their environment. In such a sense, walking is a fundamental activity that is integral to daily living, understanding the cognition during walking can provide insights into broader aspects of human cognition and brain function.

Progress in walking-related research

One major area of research has focused on how the processing of visual and auditory cues influences kinematics, such as gait, stride, postural adjustments, and head-related patterns during walking (Burtan et al., 2021; Graci, Elliott, & Buckley, 2009; Hiraoka, Kunimura, Oda, Kawasaki, & Sawaguchi, 2020; Jahn, Strupp, Schneider, Dieterich, & Brandt, 2001; Kao & Pierro, 2021). Some have also examined how auditory and visual information processing affects some cognitive processes during walking, such as obstacle avoidance, self-motion reproduction and speed estimation in and other navigation-related purposes (Jetzschke, Ernst, Froehlich, & Boeddeker, 2017; Kolarik, Scarfe, Moore, & Pardhan, 2016; Muroi & Higuchi, 2017; Silva, Aravind, Sangani, & Lamontagne, 2018; Zanchi, Cuturi, Sandini, Gori, & Ferre, 2023). Those research, although did not directly measure the influence of walking on cognitive tasks, provided some hints of how certain types of information is processed or changed by walking: for instance, the finding showing that subjects exhibit more cautious behaviour, with decreased walking speed and step length when peripheral ~~occlusion~~ vision was occluded using an eye-protective goggles suggests the importance of peripheral processing during walking (Graci, Elliott et al. 2009).

Another line of study, which assessed the influence of body movement on cognitive processing drew more and more attention in the past 10 years (for reviews, see (Schmidt-Kassow & Kaiser, 2023; Stangl, Maoz, & Suthana, 2023). These studies usually employed a classic EEG dual-task methodology and compared the EEG response between a movement condition and a static condition. This line of research has revealed some interesting findings. One is that walking is associated with a decrease in the amplitude of both visual and auditory P300 compared to standing (Bradford, Lukos, Passaro, Ries, & Ferris, 2019; Chen, Cao, & Haendel, 2022; Gramann et al., 2010; Ladouce, Donaldson, Dudchenko, & Ietswaart, 2019). Traditionally, increased P300 amplitude may indicate enhanced attention or cognitive processing resources allocated to a task, while a decreased amplitude may suggest decreased attention or cognitive load. The reduced P300 amplitude was therefore considered as neural marker of reduced attention due to cognitive-motor interference. Another widely reported finding is that walking leads to reduced ongoing parietal-occipital ongoing alpha power compared to standing, which has been repeatedly reported independent of task feature and stimulus modalities (Cao, Chen, & Haendel, 2020; Cao & Handel, 2019; Chen et al., 2022; Delaux et al., 2021; Ehinger et al., 2014; Lin, Wang, & Jung, 2014). Alpha power has been well-documented as a reflection of functional inhibition, with low alpha activity being considered as a signature of regions engaged in active neuronal processing, whereas strong alpha oscillations reflect the inhibition and disengagement of task-irrelevant cortical areas (Jensen & Mazaheri, 2010; Klimesch, 2012).The reduction of alpha power due to walking therefore might indicate a changed attentional state during walking. Some researchers have also demonstrated that specific phases of walking can influence neural and behavioural responses, as well as eye movement patterns in a different way (Davidson, Verstraten, & Alais, 2024; Hollands, Marple-Horvat, Henkes, & Rowan, 1995; Lajoie, Teasdale, Bard, & Fleury, 1993; Patla & Vickers, 2003). Overall, there

are some significant findings about how walking influences the cognitive processing, with quite some consistencies across modalities. These findings highlighted the importance of considering walking as a behavioural state in fully understanding human cognition.

Multisensory processing during walking is not well-explored

Despite the above-mentioned fruitful investigations directly or indirectly reflecting the cognitive processing during walking, both lines of studies only focused on only one individual modality, e.g. with task only including either visual or auditory task/stimuli. Relatively little work has been performed to explore how multisensory processes are integrated during walking. Even among those who have attempted to investigate multisensory processing during walking, the focus is to investigate whether one sensory modality is more important than another modality in affecting walking related activities. Vision has been found to be influential in avoiding obstacle and collisions, as well as alleviating split-belt locomotor adaptation effects, referring to the continuously adjustment of the timing and coordination of each limb by nervous system (Eikema et al., 2016; Kolarik et al., 2016; Silva et al., 2018). Some bodily sensations including vestibular, somatosensory, and proprioceptive inputs play crucial roles and can interact with visual processing to influence overall locomotor function (Cano Porras et al., 2020; Frissen, Campos, Souman, & Ernst, 2011). In some occasions, those sensations could dominate the cognitive processes during walking. Similarly, for audition, and tactile sensation, studies also still focused on how integrating perception of auditory and tactile stimuli influence walking-related patterns (Dollack, Perusquia-Hernandez, Kadone, & Suzuki, 2019; Eikema et al., 2016; Gupta, Kelty-Stephen, Mangalam, McKindles, & Stirling, 2023; Jetzschke et al., 2017; Pitman, Sutherland, & Vallis, 2021). Majority of studies still just make interpretations based on how sensory process changes walking-related patterns, direct evidence of how the human during walking process the sensory input across modalities is lacking.

Sensory processing between modalities might work in an integrated way as shown in animal models

Research based on animal models have raised some interesting research discussions and questions regarding the multisensory processing during locomotion. There are animal studies showing that, unlike the facilitatory effect of locomotion on visual cortical responses (Niell and Stryker, 2010), the activity of auditory cortical neurons is suppressed (Schneider, Nelson, & Mooney, 2014; Schneider, Sundararajan, & Mooney, 2018; Yavorska & Wehr, 2021). This suppression has been observed in studies examining both auditory cortical neurons and simultaneous recordings of auditory and visual regions of the thalamus (Williamson, Hancock, Shinn-Cunningham, & Polley, 2015). Such suppression, however, was evidenced and discussed as not just simple inhibition of external sound or self-generated sound by feet, but a reflection of a neural resource allocation shifts from audition to vision

(Schneider et al., 2014; Zhou et al., 2014) and also as tradeoff with the emergence of explicit and reliable coding of locomotion velocity (Vivaldo, Lee, Shorkey, Keerthy, & Rothschild, 2023). One review has also suggested that the suppression observed in the processing of auditory information could be associated with the reallocation of processing resources away from acoustic input but toward somatosensory or visual cues when individual actively explores the environment (Lohse, Zimmer-Harwood, Dahmen, & King, 2022). Those animal work generally suggest that during locomotion, sensory processing in different modalities might work in an integrated way to aid for the perception, possibility due the limited resources. In an even broader sense, how an individual's sensory processing influenced by locomotion is likely the result of multiple factors being modulated and weighted together. It is worth noting that while recent studies suggest similar findings in humans, there was no conclusive evidence as animal studies. Overall, this highlights the need for systematic investigation into multisensory processing.

Considering the cognition in human, in real world scenario, human almost do not walk while detecting something in a complete two-dimension panel, e.g. the screen in front, or an auditory information attached to ears in left or right. Instead, an often happen condition is to notice, reach or explore something actively while walking, multiple external sensory information can also interact with walking-generated visual, auditory and other body-related sensory input. From a fundamental science point of view, it is worth investigating whether walking negatively affects auditory behavioral task performance and neural responses to visual stimuli, as observed in animal studies. This question is closely related to how attention is allocated during walking. Practically, it is also relevant to real-world scenarios, such as how walking is allocated crossing a street or avoiding people and other obstacles. To answer these questions, it is crucial to understand how walking influences attention allocation dynamics and associated neural patterns. This area of research holds significant interest for future studies.

To summarize, recent research has made significant progress in understanding how walking influences sensory processing in individual modalities. However, questions related to multisensory processing during walking remain numerous and are not yet well explored in humans. Future research should aim to investigate how multisensory information is integrated during walking, this line of inquiry is essential for advancing our understanding of human cognition in real-world scenarios.

References:

Bradford, J. C., Lukos, J. R., Passaro, A., Ries, A., & Ferris, D. P. (2019). Effect of locomotor demands on cognitive processing. *Scientific Reports, 9*. doi:ARTN 9234
10.1038/s41598-019-45396-5

Burtan, D., Joyce, K., Burn, J. F., Handy, T. C., Ho, S., & Leonards, U. (2021). The nature effect in motion: visual exposure to environmental scenes impacts cognitive

load and human gait kinematics. *R Soc Open Sci, 8*(1), 201100. doi:10.1098/rsos.201100

Byrge, L., Sporns, O., & Smith, L. B. (2014). Developmental process emerges from extended brain-body-behavior networks. *Trends Cogn Sci, 18*(8), 395-403. doi:10.1016/j.tics.2014.04.010

Cano Porras, D., Zeilig, G., Doniger, G. M., Bahat, Y., Inzelberg, R., & Plotnik, M. (2020). Seeing Gravity: Gait Adaptations to Visual and Physical Inclines - A Virtual Reality Study. *Frontiers in Neuroscience, 13*. doi:10.3389/fnins.2019.01308

Cao, L., Chen, X., & Haendel, B. F. (2020). Overground Walking Decreases Alpha Activity and Entrains Eye Movements in Humans. *Front Hum Neurosci, 14*, 561755. doi:10.3389/fnhum.2020.561755

Cao, L., & Handel, B. (2019). Walking enhances peripheral visual processing in humans. *PLoS Biol, 17*(10), e3000511. doi:10.1371/journal.pbio.3000511

Chen, X., Cao, L., & Haendel, B. F. (2022). Human visual processing during walking: Dissociable pre- and post-stimulus influences. *Neuroimage, 264*, 119757. doi:10.1016/j.neuroimage.2022.119757

Chiel, H. J., & Beer, R. D. (1997). The brain has a body: adaptive behavior emerges from interactions of nervous system, body and environment. *Trends Neurosci, 20*(12), 553-557. doi:10.1016/s0166-2236(97)01149-1

Davidson, M. J., Verstraten, F. A. J., & Alais, D. (2024). Walking modulates visual detection performance according to stride cycle phase. *Nat Commun, 15*(1), 2027. doi:10.1038/s41467-024-45780-4

Debener, S., Minow, F., Emkes, R., Gandras, K., & De Vos, M. (2012). How about taking a low-cost, small, and wireless EEG for a walk? *Psychophysiology, 49*(11), 1617-1621. doi:10.1111/j.1469-8986.2012.01471.x

Delaux, A., de Saint Aubert, J. B., Ramanoel, S., Becu, M., Gehrke, L., Klug, M., . . . Arleo, A. (2021). Mobile brain/body imaging of landmark-based navigation with high-density EEG. *Eur J Neurosci, 54*(12), 8256-8282. doi:10.1111/ejn.15190

Dollack, F., Perusquia-Hernandez, M., Kadone, H., & Suzuki, K. (2019). Head Anticipation During Locomotion With Auditory Instruction in the Presence and Absence of Visual Input. *Front Hum Neurosci, 13*, 293. doi:10.3389/fnhum.2019.00293

Ehinger, B. V., Fischer, P., Gert, A. L., Kaufhold, L., Weber, F., Pipa, G., & Konig, P. (2014). Kinesthetic and vestibular information modulate alpha activity during spatial navigation: a mobile EEG study. *Front Hum Neurosci, 8*, 71. doi:10.3389/fnhum.2014.00071

Eikema, D. J., Chien, J. H., Stergiou, N., Myers, S. A., Scott-Pandorf, M. M., Bloomberg, J. J., & Mukherjee, M. (2016). Optic flow improves adaptability of spatiotemporal characteristics during split-belt locomotor adaptation with tactile stimulation. *Exp Brain Res, 234*(2), 511-522. doi:10.1007/s00221-015-4484-5

Frissen, I., Campos, J. L., Souman, J. L., & Ernst, M. O. (2011). Integration of vestibular and proprioceptive signals for spatial updating. *Experimental Brain Research,*

212(2), 163-176. doi:10.1007/s00221-011-2717-9

Graci, V., Elliott, D. B., & Buckley, J. G. (2009). Peripheral visual cues affect minimum-foot-clearance during overground locomotion. *Gait Posture, 30*(3), 370-374. doi:10.1016/j.gaitpost.2009.06.011

Gramann, K., Gwin, J. T., Bigdely-Shamlo, N., Ferris, D. P., & Makeig, S. (2010). Visual evoked responses during standing and walking. *Frontiers in Human Neuroscience, 4*. doi:ARTN 20210.3389/fnhum.2010.00202

Gupta, A., Kelty-Stephen, D. G., Mangalam, M., McKindles, R. J., & Stirling, L. (2023). Walking speed and dual task input modality impact performance on a self-paced treadmill. *Appl Ergon, 109*, 103986. doi:10.1016/j.apergo.2023.103986

Hiraoka, K., Kunimura, H., Oda, H., Kawasaki, T., & Sawaguchi, Y. (2020). Rhythmic movement and rhythmic auditory cues enhance anticipatory postural adjustment of gait initiation. *Somatosens Mot Res, 37*(3), 213-221. doi:10.1080/08990220.2020.1777959

Hollands, M. A., Marple-Horvat, D. E., Henkes, S., & Rowan, A. K. (1995). Human Eye Movements During Visually Guided Stepping. *J Mot Behav, 27*(2), 155-163. doi:10.1080/00222895.1995.9941707

Jahn, K., Strupp, M., Schneider, E., Dieterich, M., & Brandt, T. (2001). Visually induced gait deviations during different locomotion speeds. *Exp Brain Res, 141*(3), 370-374. doi:10.1007/s002210100884

Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: gating by inhibition. *Front Hum Neurosci, 4*, 186. doi:10.3389/fnhum.2010.00186

Jetzschke, S., Ernst, M. O., Froehlich, J., & Boeddeker, N. (2017). Finding Home: Landmark Ambiguity in Human Navigation. *Frontiers in Behavioral Neuroscience, 11*. doi:10.3389/fnbeh.2017.00132

Kao, P. C., & Pierro, M. A. (2021). Dual-task treadmill walking at self-paced versus fixed speeds. *Gait Posture, 89*, 92-101. doi:10.1016/j.gaitpost.2021.07.001

Klimesch, W. (2012). alpha-band oscillations, attention, and controlled access to stored information. *Trends Cogn Sci, 16*(12), 606-617. doi:10.1016/j.tics.2012.10.007

Kolarik, A. J., Scarfe, A. C., Moore, B. C., & Pardhan, S. (2016). An assessment of auditory-guided locomotion in an obstacle circumvention task. *Exp Brain Res, 234*(6), 1725-1735. doi:10.1007/s00221-016-4567-y

Ladouce, S., Donaldson, D. I., Dudchenko, P. A., & Ietswaart, M. (2019). Mobile EEG identifies the re-allocation of attention during real-world activity. *Sci Rep, 9*(1), 15851. doi:10.1038/s41598-019-51996-y

Lajoie, Y., Teasdale, N., Bard, C., & Fleury, M. (1993). Attentional demands for static and dynamic equilibrium. *Exp Brain Res, 97*(1), 139-144. doi:10.1007/BF00228824

Lin, Y. P., Wang, Y., & Jung, T. P. (2014). Assessing the feasibility of online SSVEP decoding in human walking using a consumer EEG headset. *J Neuroeng Rehabil, 11*, 119. doi:10.1186/1743-0003-11-119

Lohse, M., Zimmer-Harwood, P., Dahmen, J. C., & King, A. J. (2022). Integration of

somatosensory and motor-related information in the auditory system. *Front Neurosci, 16*, 1010211. doi:10.3389/fnins.2022.1010211

Muroi, D., & Higuchi, T. (2017). Walking through an aperture with visual information obtained at a distance. *Exp Brain Res, 235*(1), 219-230. doi:10.1007/s00221-016-4781-7

Patla, A. E., & Vickers, J. N. (2003). How far ahead do we look when required to step on specific locations in the travel path during locomotion? *Exp Brain Res, 148*(1), 133-138. doi:10.1007/s00221-002-1246-y

Pitman, J., Sutherland, K., & Vallis, L. A. (2021). Exploring the cognitive demands required for young adults to adjust online obstacle avoidance strategies. *Exp Brain Res, 239*(3), 1009-1019. doi:10.1007/s00221-020-06006-3

Schmidt-Kassow, M., & Kaiser, J. (2023). The brain in motion-cognitive effects of simultaneous motor activity. *Frontiers in Integrative Neuroscience, 17*. doi:ARTN 1127310

10.3389/fnint.2023.1127310

Schneider, D. M., Nelson, A., & Mooney, R. (2014). A synaptic and circuit basis for corollary discharge in the auditory cortex. *Nature, 513*(7517), 189-194. doi:10.1038/nature13724

Schneider, D. M., Sundararajan, J., & Mooney, R. (2018). A cortical filter that learns to suppress the acoustic consequences of movement. *Nature, 561*(7723), 391-395. doi:10.1038/s41586-018-0520-5

Silva, W. S., Aravind, G., Sangani, S., & Lamontagne, A. (2018). Healthy young adults implement distinctive avoidance strategies while walking and circumventing virtual human vs. non-human obstacles in a virtual environment. *Gait & Posture, 61*, 294-300. doi:10.1016/j.gaitpost.2018.01.028

Stangl, M., Maoz, S. L., & Suthana, N. (2023). Mobile cognition: imaging the human brain in the 'real world'. *Nat Rev Neurosci, 24*(6), 347-362. doi:10.1038/s41583-023-00692-y

Vivaldo, C. A., Lee, J., Shorkey, M., Keerthy, A., & Rothschild, G. (2023). Auditory cortex ensembles jointly encode sound and locomotion speed to support sound perception during movement. *PLoS Biol, 21*(8), e3002277. doi:10.1371/journal.pbio.3002277

Williamson, R. S., Hancock, K. E., Shinn-Cunningham, B. G., & Polley, D. B. (2015). Locomotion and Task Demands Differentially Modulate Thalamic Audiovisual Processing during Active Search. *Current Biology, 25*(14), 1885-1891. doi:10.1016/j.cub.2015.05.045

Wilson, M. (2002). Six views of embodied cognition. *Psychon Bull Rev, 9*(4), 625-636. doi:10.3758/bf03196322

Yavorska, I., & Wehr, M. (2021). Effects of Locomotion in Auditory Cortex Are Not Mediated by the VIP Network. *Front Neural Circuits, 15*, 618881. doi:10.3389/fncir.2021.618881

Zanchi, S., Cuturi, L. F., Sandini, G., Gori, M., & Ferre, E. R. (2023). Vestibular contribution to spatial encoding. *Eur J Neurosci, 58*(9), 4034-4042. doi:10.1111/ejn.16146

Zhou, M., Liang, F., Xiong, X. R., Li, L., Li, H., Xiao, Z., . . . Zhang, L. I. (2014). Scaling down of balanced excitation and inhibition by active behavioral states in auditory cortex. *Nat Neurosci, 17*(6), 841-850. doi:10.1038/nn.3701